Analysis of heat transfer on CRUD by using the CUPID-RV/GIFT coupled code

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1. Introduction

As the discharge burnup of nuclear fuel increases, fuel exhibits deformation such as oxidation and hydrogen embrittlement[1]. To address these phenomena, regulatory bodies are revising the ECCS acceptance criteria, which require accounting for the fuel deformation and the thermal resistance of the CRUD and oxide layer[2-3]. Consequently, multi-physics analysis that can consider detailed fuel behavior has become important.

In a previous study, the subchannel analysis code CUPID-RV developed by KAERI and the fuel performance code GIFT developed by SNU were coupled to enable steady-state analysis considering both fuel deformation and thermal-hydraulics[4]. However, this framework did not yet consider the effect of CRUD.

In high burnup reactor environments, a porous structure of corrosion product known as CRUD is formed on the fuel cladding surface. This structure acts as a thermal resistance layer with low thermal conductivity. However, the porous structure constantly supplies coolant to the cladding surface by capillary action and enhances evaporation. Therefore, these competing phenomena affect heat transfer on CRUD. Also, this mechanism affects fuel deformation or reactor power as well. Therefore, the effect of CRUD on heat transfer should be considered in multi-physics analysis.

This study aims to conduct a comprehensive multi-physics analysis of the effect of the CRUD deposits. To achieve this analysis, a CRUD heat transfer model was implemented into the CUPID-RV code. The simulation was conducted for a single fuel assembly to evaluate the effect of the CRUD heat transfer model on fuel condition using the CUPID-RV/ GIFT coupled code. In addition, a full-core simulation was conducted to estimate temperature change by CRUD using the standalone CUPID-RV code.

2. Methods

In this section, a model describing heat transfer within CRUD and its application to the CUPID-RV code will be introduced.

2.1 CRUD heat transfer model

In the high burnup fuel, a porous structure of corrosion product called CRUD is formed on the cladding surface. This layer can act as a thermal resistance. However, when the temperature within CRUD increases, the enhanced evaporation, known as wick boiling, occurs within CRUD. In this process, generated vapor evacuates through large pores called a chimney, while capillary force supplies coolant to the cladding surface through small pores. This wick boiling enhances heat transfer within the CRUD layer and competes with the thermal resistance effect.

Several CRUD heat transfer models have been developed to simulate wick boiling phenomena[5-8]. The Yeo model[8] was selected and applied to the CUPID-RV code. Fig. 1 is a schematic of the heat transfer mechanism of the Yeo model. In the Yeo model, the CRUD layer is divided into two regions, the thermal boundary layer and the wick region. The thermal boundary layer is the region where evaporation occurs, and bubble grows. The rest of the region is called the wick region. The heat is transferred through evaporation at the cladding surface in the thermal boundary layer and conduction and convection within the wick region.

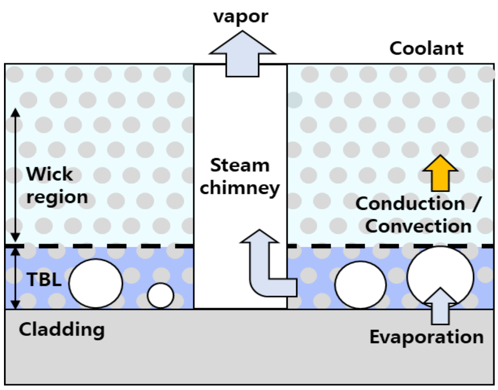

Fig. 1 Schematic of the Yeo model

The Forster-Zuber pool boiling correlation[9] is used to predict the evaporative heat flux at the thermal boundary layer, as shown in Eqn. 1. Where q''_{evap} is the evaporative heat flux, and T_{clad} is the cladding temperature. The coefficient c_b is determined based on the WALT experimental results[10], as presented in Eqn. 2. Where μ_f is the coolant viscosity, h_{fg} is the latent heat of the coolant, ρ_f is the coolant density, c_p is the coolant heat capacity, σ_f is the surface tension, T_{sat} is the saturation temperature of the coolant, and v_{fg} is the specific volume difference between saturated liquid and vapor. k_{eff} is the effective thermal conductivity within

CRUD. The CRUD heat transfer model treats the CRUD layer as a single thermal structure with an effective thermal conductivity, assuming thermal equilibrium between the water and the metallic deposit within the CRUD layer. The effective thermal conductivity of CRUD is affected by its porosity[5].

$$q''_{evap} = c_b(T_{clad} - T_{sat})^{0.75} \tag{1}$$

$$c_b = 2.43 \times 10^{-4}\left(\frac{\mu_f^{1/3} k_{eff}^{1/6} h_{fg}^{7/4}}{\rho_f^{3/4} c_p^{1/6} \sigma_f^{1/2} T_{sat}^{3/4} v_{fg}^{7/4}}\right) \tag{2}$$

Since the thermal boundary layer is very thin, the temperature gradient within this region is assumed to be linear. The temperature distribution inside the thermal boundary layer is calculated using Eqn. 3. Where q''_{clad} is the heat from the cladding surface, f_v is the area fraction of heated surface occupied by the chimneys, and δ_{TBL} is the thickness of the thermal boundary layer.

$$\frac{dT}{dx} = \frac{q''_{clad}}{(1-f_v)k_{eff}} = \frac{T_{clad} - T_{sat}}{\delta_{TBL}} \tag{3}$$

And the temperature distribution within the wick region is calculated using Eqn. 4. Where u_f is the liquid velocity generated by the capillary force within a porous structure.

$$\frac{d}{dx}\left(k_{eff}\frac{dT}{dx}\right) = \rho_f c_p u_f \frac{dT}{dx} \tag{4}$$

2.2 Parametric study of the CRUD heat transfer model

A parametric study was conducted to evaluate the model by varying key geometric parameters of CRUD. The thermal-hydraulic boundary conditions and the geometric parameters of CRUD are summarized in Table. 1.

Table. 1 Input conditions for parametric study

Parameters	Value
System pressure [MPa]	15.5
Bulk coolant temperature [K]	600
Chimney radius [μm]	2.5
Chimney density [#/mm2]	3000
CRUD thickness [μm]	50
CRUD porosity [-]	0.5

Fig. 2 and Fig. 3 show the predicted cladding temperature along the heat flux with various ranges of the CRUD thickness and porosity.

Fig. 2 shows the effect of CRUD thickness on the cladding temperature. Higher cladding temperatures were predicted in a thicker CRUD condition due to the increased thermal resistance.

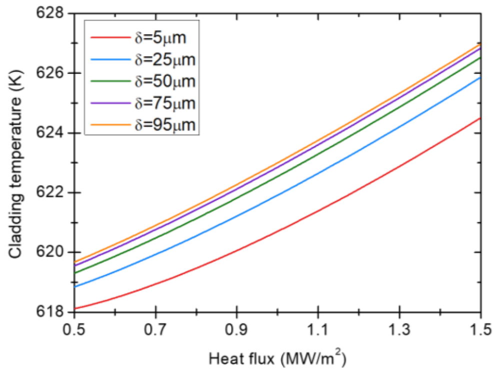

Fig. 2 Effect of the CRUD thickness on cladding temperature in the CRUD heat transfer model

Fig. 3 shows the effect of the CRUD porosity on the cladding temperature. Higher cladding temperatures were predicted in the higher porosity conditions. In a higher porosity condition, more liquid fraction is formed in the CRUD layer. Since the liquid has a lower thermal conductivity than the solid structure, the effective thermal conductivity of CRUD decreases. This increases the overall thermal resistance, resulting in a higher cladding temperature.

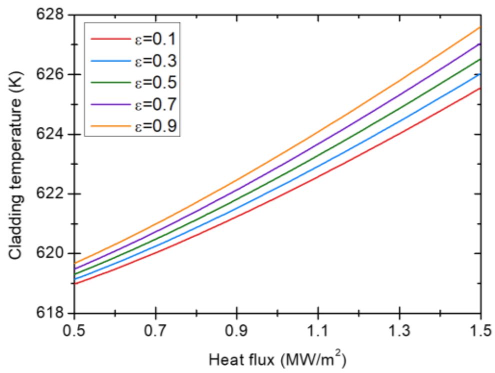

Fig. 3 Effect of the CRUD porosity on cladding temperature in the CRUD heat transfer model

2.3 Implementation of the CRUD heat transfer model into the CUPID-RV

The CRUD heat transfer model was implemented into the CUPID-RV code to account for the effects of CRUD on the high burnup fuel surface. The single-phase convection and nucleate boiling heat transfer models in the CUPID-RV were replaced with the CRUD heat transfer model, as shown in Fig. 4. The model was validated against a boiling experiment on a CRUD deposited surface.

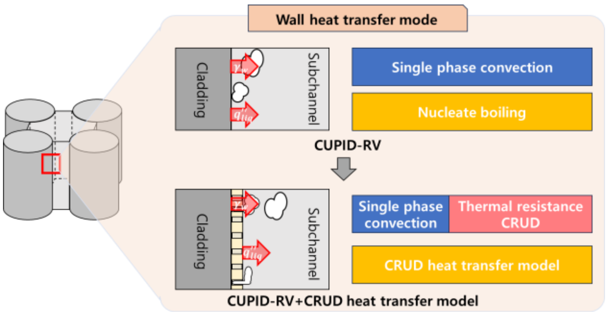

Fig. 4 Implementation process of the CRUD heat transfer model into the CUPID-RV

2.4 Validation of the CRUD heat transfer model

WALT (Westinghouse Advanced Loop Tester)[10] is an experimental facility used to investigate the CRUD deposition and its material properties under the operational conditions of PWRs. Structural, chemical characteristics, and thermal conductivity of CRUD were examined.

Although these experiments were primarily designed to measure the effective thermal conductivity under single-phase conditions, some experiments exhibited evaporation that reflected wick boiling effect. The conditions for these evaporation experiments are detailed in Table. 2, and the experimental results were used to validate the CUPID-RV code incorporating the CRUD heat transfer model.

Table. 2 Experiment condition of the WALT boiling cases

Parameters	Case 1	Case 2	Case 3
CRUD thickness [μm]	52.75	74.25	65.67
CRUD porosity [-]	0.60	0.63	0.73
Chimney radius [μm]	2	4	3
Chimney density [#/mm2]	1300	570	480
Inlet coolant temperature [K]	608	600	563
Mass flux [kg/m^{2}s]	2578.4	1633.8	1589.2
Exit pressure [MPa]	15.6	15.5	15.6

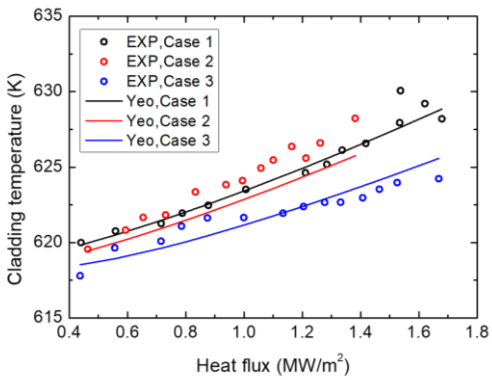

Fig. 5 Validation of the CUPID-RV with the CRUD heat transfer model against boiling cases of the WALT experiment

Fig. 5 shows the validation of the CUPID-RV code with the CRUD heat transfer model against boiling cases of the WALT experiments. Overall, the results showed good agreement with the experimental data. However, the cladding temperature for case 2 is underpredicted by up to 3 K.

In the validation simulation, the effective thermal conductivity of CRUD proposed by EPRI was used, which was derived from the average of the WALT experimental results. Consequently, a discrepancy in thermal conductivity may exist between the experiment and the simulation, resulting in underprediction in case 2.

3. Results

3.1 Evaluation of the effect of the CRUD heat transfer model on fuel deformation

In a previous study, the CUPID-RV/GIFT coupled code was developed to account for the effect of the fuel deformation in thermal-hydraulic analysis[4]. In this study, the CRUD heat transfer model was also implemented into the CUPID-RV/GIFT coupled code to evaluate how fuel deformation is affected by the presence of CRUD.

In the CUPID-RV, the CRUD heat transfer model is used to calculate the temperature distribution within the CRUD layer, and GIFT produces the CRUD thickness data. Coupled variables exchanged between the CUPID-RV and the GIFT are shown in Fig. 6.

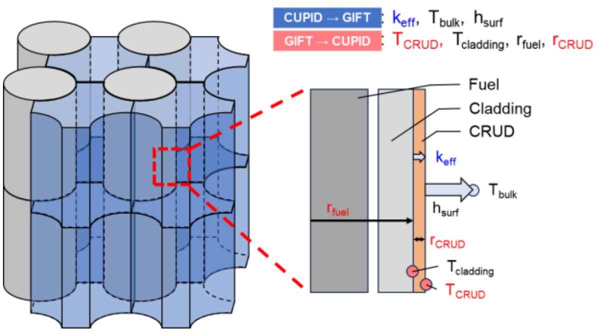

Fig. 6 Data exchange scheme in the CUPID-RV/GIFT

To analyze the effect of the CRUD heat transfer model on fuel deformation, a simulation for a hot assembly of the WBN1 (Watts Bar Nuclear Unit 1) reactor was performed. The simulation used single cycle power distribution data calculated by coupled analysis of the CUPID-RV with the nTER, neutron transport code developed by KAERI[11]. The CRUD thickness was modeled as a simple linear function of power and EFPD, based on the CRUD deposition data calculated by the BOTANI code[12], a simulation code for the CRUD deposition and boron accumulation developed by SNU, as shown in Fig. 8. The geometric parameters of CRUD and the thermal-hydraulic boundary conditions used in the analysis are summarized in Table. 3 and Table. 4, respectively.

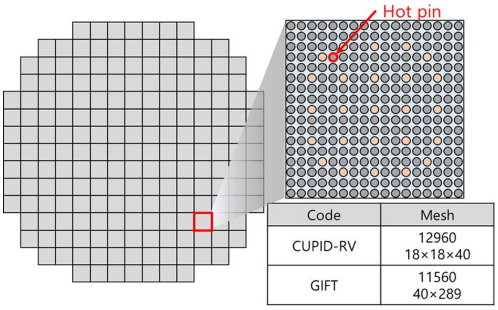

Fig. 7 Schematic of WH type core geometry, fuel assembly, and mesh information

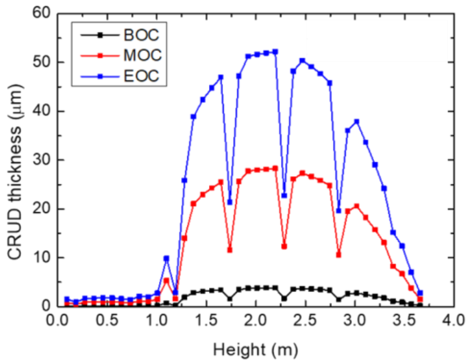

Fig. 8 CRUD thickness modeled in the CUPID-RV/GIFT

Table. 3 CRUD geometric parameters used in hot assembly analysis

Parameters	Value
Porosity [-]	0.6
Chimney radius [μm]	3
Chimney density [#/mm^2]	5000

Table. 4 Thermal-hydraulic boundary conditions in hot assembly analysis

Parameters	Value
System pressure [MPa]	15.5
Inlet coolant temperature [K]	565
Mass flux [kg/m^{2}s]	3535.24

To evaluate the effect of CRUD on heat transfer and fuel deformation, the cladding temperature and thickness of the oxide layer were examined, as shown in Fig. 9.

The cladding temperature and oxidation thickness were compared for the cases with and without CRUD, as shown in Fig. 10. In the case without CRUD, the cladding temperature increases along the axial direction without boiling. In contrast, in the case with CRUD, a generally higher cladding temperature is observed due to the thermal resistance effect of CRUD. When the cladding temperature reaches the saturation temperature, wick boiling occurs and enhances heat transfer, subsequently stabilizing the temperature profile. Consequently, the maximum difference is observed in the lower regions of the assembly where wick boiling initiates, as shown in Fig. 11.

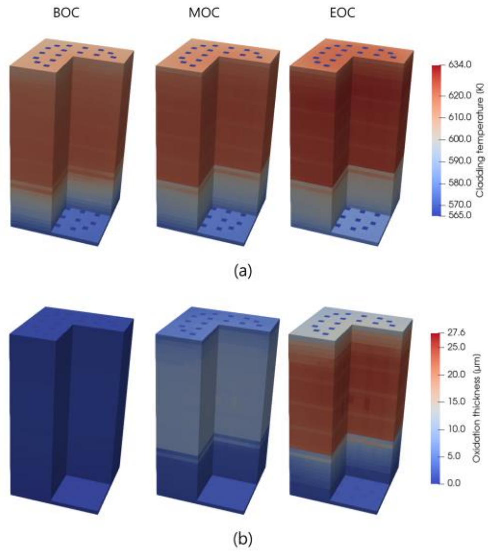

Fig. 9 Simulation result of the CUPID-RV/GIFT coupled code considering the CRUD heat transfer
(a) Cladding temperature, (b) Oxidation Thickness

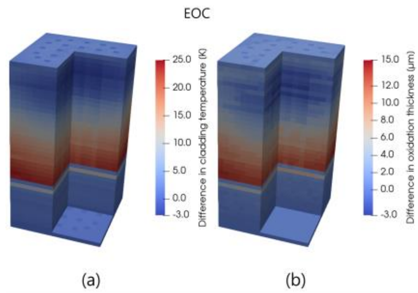

Fig. 10 Property differences between the cases with CRUD and without CRUD at the EOC
(a) Cladding temperature, (b) Oxidation Thickness

To further analyze the effect of the CRUD heat transfer model, an analysis was performed on a hot pin at the EOC. Three simulations were compared, a case without CRUD, a case with CRUD that acts only as a thermal resistance without considering wick boiling, and a case with CRUD considering wick boiling to investigate the effect of wick boiling.

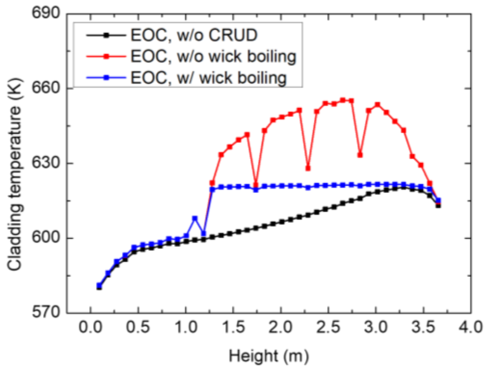

Fig. 11 Cladding temperature of the hot pin at the EOC

The simulation results for cladding temperature are shown in Fig. 11. The presence of CRUD increases the cladding temperature due to the low effective thermal conductivity of CRUD around 0.8 W/mK. However, the magnitude of this temperature rise is significantly reduced when wick boiling is considered.

A similar trend is observed for the oxidation thickness. As shown in Fig. 12, the thickness of oxide significantly increased in the case of CRUD without wick boiling, and the increase in oxidation thickness is suppressed when wick boiling is considered.

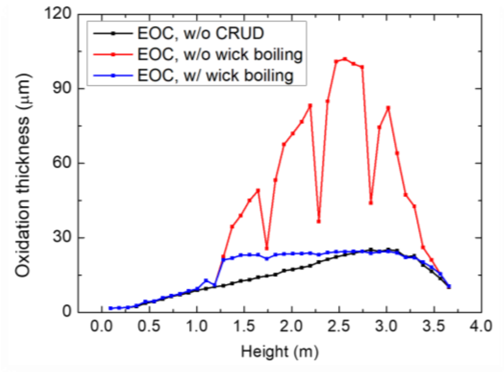

Fig. 12 Oxidation thickness of the hot pin at the EOC

3.2 Preliminary simulation for extension to the full core analysis for the effect of the CRUD heat transfer model

For further analysis, a first cycle simulation of the full core of the OPR1000 reactor was conducted. Due to the excessive computational cost of the coupled simulation with GIFT, the full core analysis was performed using the standalone CUPID-RV code to investigate the trend of the effect of CRUD on heat transfer. The power history of the first cycle of the OPR1000 reactor was obtained from the simulation results of a CUPID-RV/MASTER/GIFT full core analysis, a coupled analysis of thermal-hydraulics, neutron-kinetics, and fuel performance code[13]. The calculational meshes information is described in Fig. 13. The geometrical parameters for CRUD and the thermal-hydraulic boundary conditions used in the full core analysis were set to be identical to those for the hot assembly analysis, as presented in Table. 3 and Table. 4, respectively.

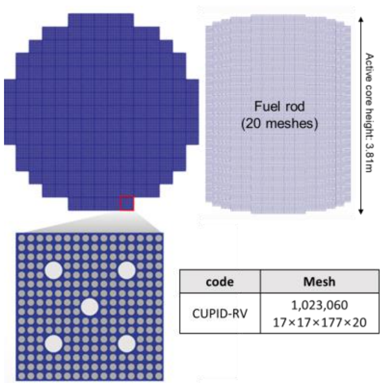

Fig. 13. Schematic of OPR1000 reactor core geometry, fuel assembly, and mesh information

The simulation results are presented in Fig. 14, which compares the cladding temperature for cases without CRUD and with CRUD and the CRUD heat transfer model. At the EOC, the cladding temperature increases by a maximum of 24.3K at the axial center of the core, where the thickest CRUD layer is formed. However, the temperature decreased due to wick boiling at the top of the core. In this region the CRUD deposition is relatively low. Therefore, the thermal resistance is relatively low. In contrast, wick boiling enhanced evaporation in the cladding surface at the top of the core. Between these two competing effects, the effect of wick boiling was more dominant, resulting in a lower cladding temperature at the top of the core.

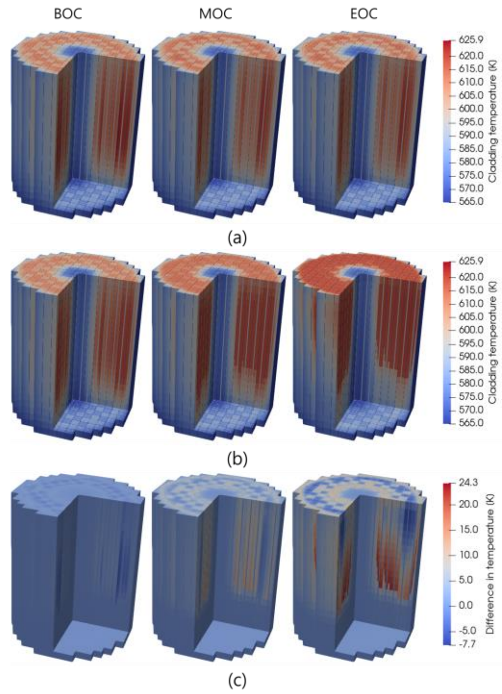

Fig 14. Simulation result of cladding temperature under the condition of (a) w/o CRUD, (b) w CRUD, and (c) the cladding temperature difference between (a) and (b)

In contrast, in the case without CRUD, boiling did not occur due to the low bulk temperature. Since the heat transfer condition does not exceed the net vapor generation point, heat is transferred through single-phase convection. However, the CRUD heat transfer model assumes that coolant reaches thermal equilibrium with the metallic deposit of CRUD when the coolant is absorbed into CRUD. Consequently, saturated or superheated coolant is constantly supplied to the coolant surface, leading to wick boiling despite the low bulk coolant temperature. As shown in Fig. 15, evaporation occurred more actively in the case with CRUD. This effect should be further analyzed as future work.

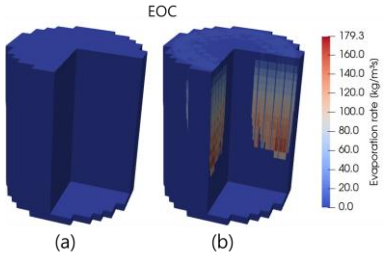

Fig. 15 Evaporation rate at the EOC under the condition of (a) w/o CRUD, (b) w/ CRUD

4. Conclusions

In this study, to analyze the effects of CRUD on the heat transfer and fuel deformation of the high burnup fuel cladding, the CRUD heat transfer model was implemented into the CUPID-RV.

A single cycle assembly simulation was conducted, and it was confirmed that the presence of CRUD leads to an increase in cladding temperature and a corresponding growth in the oxide layer thickness.

Furthermore, a single cycle full core simulation was conducted using the standalone CUPID-RV code. As a result, a temperature increase at the axial center of the core was observed, and a temperature decrease in the upper region was observed as well.

Further validation of the CRUD heat transfer model under a broader range of pressure conditions and for the various CRUD deposition scenarios is required.

Acknowledgments

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REFERENCES

[1] M. Bruet et al., "High Burnup Fuel Behavior During a LOCA Type Accident: the FLASH-5 Experiment", IAEA Technical Committee Meeting on Behavior of Core Material and Fission Products Release in Accident Conditions in LWRs, Cadarache, France, 1982.

[2] J.S. Lee et al., "Technical Basis for the Revision of ECCS Acceptance Criteria of Domestic PWR Plants", KINS/RR1686, KINS, 2017.

[3] US NRC, "Performance-Based Emergency Core Cooling System Requirements and Related Fuel Cladding Criteria", 2016.

[4] Y.H.Lee et al., "Coupled simulation for pin-wise reactor core analysis using subchannel analysis code CUPID and fuel performance code GIFT", Annals of Nuclear Energy 213, 2025.

[5] C. Pan et al., "Concentration levels of solutes in porous deposits with chimneys under wick boiling conditions", Nuclear Engineering and Design 99, 1987.

[6] V.K. Dhir, "Complete numerical simulation of subcooled flow boiling in the presence of thermal and chemical interactions", DOE grant No.DE-FG03-99SF-21930, 2003.

[7] B.G. Jones, et al., "Modeling and thermal performance evaluation of porous crud layers in subcooled boiling region of PWRs and effects of sub-cooled nucleate boiling on anomalous porous crud deposition on fuel pin surfaces", DOE DEFG07-001D13924, 2005.

[8] D.Y. Yeo and H.C. NO, "Modeling heat transfer through chimney-structured porous deposit formed in pressurized water reactors", International Journal of Heat and Mass Transfer 108, 2017.

[9] H. Forster, N. Zuber, "Dynamics of vapor bubbles and boiling heat transfer", AlChe J. 1 531-535, 1955.

[10] J. Deshon, "Simulated Fuel Crud Thermal Conductivity Measurements Under Pressurized Water Reactor Conditions", EPRI, Palo Alto, CA:2011. 1022896, 2011.

[11] Y.Y. Choi, et al., "Multi-physics Solution of VERA Core Physics Benchmark using CUPID and nTER", Transaction of the Korean Nuclear Society Autumn Meeting, Goyang, Korea, 2019.

[12] S.J. Seo, et al., "Modeling of deposition and erosion of CRUD on fuel surfaces under sub-cooled nucleate boiling in PWR", Nuclear Engineering and Technology 55, 2023.

[13] Y.H. Lee, et al., "Preliminary Pin-wise Multi-physics Simulation using CUPID Subchannel Module Coupled with Neutron Kinetics Code and Fuel Performance Code", in Advances in Thermal Hydraulics Proceedings of 2024 ANS winter meeting, Orlando, FL, 2024.